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Quantifying the Impact of Aircraft Cannibalization

C. Richard Cassady
Alejandro Mendoza
Stephen Ormon
Kellie Schneider
Chase Rainwater
Mauricio Carrasco
Jonathan Crawford
Jason Honeycutt

University of Arkansas
Department of Industrial Engineering
4207 Bell Engineering Center
Fayetteville, AR 72701

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FOR THE COMMANDER

//SIGNED//

DANIEL R. WALKER, Colonel, USAF
Chief, Warfighter Readiness Research Division
Human Effectiveness Directorate

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14. ABSTRACT

The primary objective of this project was to develop a mathematical modeling methodology for assessing the impact of cannibalization on fleet performance in order to identify policies for making effective cannibalization decisions and to study the impact of these policies on management of the spare parts supply chain. To achieve this objective, we pursued two research avenues in parallel. First, we developed and analyzed a "generic" cannibalization model. This discrete-event simulation model was used to investigate two key issues related to aircraft readiness: cannibalization and spare parts inventory levels. Second, we developed and analyzed two discrete-event simulation models based on the cannibalization practices that take place at Hill AFB. These models were used to investigate several key issues raised by USAF officers experienced with conditions similar to those existing at Hill AFB.

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Contents

Figures

Tables

Executive Summary

Fleet aircraft maintenance involves a variety of activities that are intended to maximize the readiness of the fleet without violating budgetary constraints. One such activity is cannibalization. Because of the military's focus on fleet readiness and the expense of maintaining large spare parts inventories, all military services rely extensively on cannibalization and consider it to be a normal part of fleet maintenance. A recent five-year study identified approximately 850,000 documented US Air Force and Navy cannibalizations, which consumed 5.3 million maintenance hours. Due to the lack of available spare parts and unpredictable lead times from depot to base, aircraft are intentionally cannibalized to return hangar queens to service and maintain an acceptable level of aircraft readiness.

The primary objective of this project is to develop a mathematical modeling methodology for assessing the impact of cannibalization on fleet performance in order to identify policies for making effective cannibalization decisions and to study the impact of these policies on management of the spare parts supply chain. To achieve this objective, we pursue two research avenues in parallel. First, we develop and analyze a "generic" cannibalization model. This discrete-event simulation model is used to investigate two key issues related to aircraft readiness: cannibalization and spare parts inventory levels. The results of this investigation indicate that cannibalization can solve fleet readiness problems, but these same results support the contention that minimal investments in spare parts inventories can provide the same readiness benefits without the additional labor requirements.

Second, we develop and analyze two discrete-event simulation models based upon the cannibalization practices that take place at Hill AFB. These models are used to investigate several key issues raised by USAF officers experienced with conditions similar to those existing at Hill AFB. The results of this investigation imply that:
1. Consolidating cannibalization actions using a cannibalization (CANN) dock is superior to maintaining a cannibalization (CANN) bird at each aircraft maintenance unit (AMU)
2. The appropriate number of CANN birds for Hill AFB is 2

3. Reducing the CANN bird duration at Hill AFB to 30 days should increase the average aircraft readiness.

1 Introduction

Fleet aircraft maintenance involves a variety of activities intended to maximize the readiness of the fleet without violating budgetary constraints. One such activity is cannibalization. While cannibalization provides a short-term fix that makes one aircraft available, its long-term effects can be significant. Because of the military's focus on fleet readiness and the expense of maintaining large spare parts inventories, all military services rely extensively on cannibalization and consider it to be a normal part of fleet maintenance. A recent five-year study identified approximately 850,000 documented US Air Force and Navy cannibalizations, which consumed 5.3 million maintenance hours (equivalent to 500 aircraft maintenance personnel working full-time for five years) [1]. The United States General Accounting Office [2] recently outlined the preliminary results of a thorough study on the military services' practice of cannibalization. One of the main conclusions from this study is that current cannibalization rates are highly underestimated and that a small group of aircraft accounts for the majority of cannibalization actions.

Air Force Instruction AFI 21-101, Aerospace Equipment Maintenance Management, identifies three categories of "hangar queens" based upon the number of days since the aircraft has flown. AFI 21-101 further requires that USAF major commands (MAJCOMs) establish programs to manage hangar queens and specific management actions for each category. Because hangar queen status is a reportable metric, leadership in all the MAJCOMs place considerable emphasis on ensuring that aircraft spend as little time as possible as hangar queens. For example, Air Combat Command (ACC) Supplement 1 to AFI 21-101 identifies three categories of hangar queens: Category 1 (aircraft has not flown for 31-44 days), Category 2 (aircraft has not flown for 45-59 days), and Category 3 (aircraft has not flown for 60 or more days). These policies, combined with the lack of available spare parts and unpredictable lead times from depot to base, result in aircraft being intentionally cannibalized to return hangar queens to service and maintain an acceptable level of aircraft readiness.

The primary objective of this project is to develop a mathematical modeling methodology for assessing the impact of cannibalization on fleet performance in order to identify policies for

making effective cannibalization decisions and to study the impact of these policies on management of the spare parts supply chain. To achieve this objective, we pursue two research avenues in parallel. First, we develop and analyze a "generic" cannibalization model. This discrete-event simulation model is used to investigate two key issues related to aircraft readiness: cannibalization and spare parts inventory levels. Second, we develop and analyze two discrete-event simulation models based on the cannibalization practices that take place at Hill AFB. These models are used to investigate several key issues raised by USAF officers experienced with conditions similar to those existing at Hill AFB.

The remainder of this report is organized as follows. In Section 2, the relevant literature on cannibalization is summarized. Section 3 contains a detailed description of the development and analysis of the generic model. Section 4 contains similar information regarding the "Hill-based" models. Finally, Section 5 contains a description of future opportunities.

2 Literature Review

The relevant literature on cannibalization can be divided into two groups: governmental studies and academic studies using mathematical models. We summarize the key work in both groups.

2.1 Governmental Reports

The CNA Corporation [8] presents a formal report summarizing the effectiveness of current aircraft readiness performance metrics used in the Navy based on consolidating all maintenance actions together. The report recommends that some maintenance activities warrant separate performance measures to become effective. One of the maintenance activities currently in the consolidated group is cannibalization. The Navy currently measures cannibalization rates per 100 flying hours and cannibalization is not formally documented until after the cannibalization action is complete. This report suggests that cannibalization activities be separated into the following three categories: troubleshooting, directed by higher authority, and lack of replacement material. Each of these cannibalization actions has different impacts on both aircraft readiness and spare parts supply. Also, the report recommends that cannibalization actions be formally documented when they are initiated rather than completed. Finally, the report recommends that metrics be focused more on the supply chain (fill rates) and not just on aircraft availability.

The United States General Accounting Office [2] outlines preliminary results of a thorough study on the military services' practice of cannibalization. As stated earlier, two of the main conclusions from this study are that current cannibalization rates are highly underestimated, and that a small group of aircraft accounts for the majority of cannibalization actions. This report indicates that, because cannibalization actions take at least twice as much time to perform as repair actions, maintenance crews are forced to work a significant amount of overtime. Furthermore, the report suggests that the more an aircraft is cannibalized, the more likely other components that are in close proximity to the cannibalized part will fail. The report concludes that this environment greatly reduces maintenance workers' morale. The report identifies low spare parts inventories, unpredictable depot-to-base lead times, and component reliabilities that are less than predicted as the core reasons for the extensive use of cannibalization; however, the report recognizes that cannibalization actions are among the key reasons for maintaining

readiness rates at acceptable levels. Other identified reasons for cannibalization are: lack of experience and insufficient training of maintenance personnel, outdated maintenance manuals, and lack of testing equipment.

2.2 Academic Studies Using Mathematical Models

There is a significant amount of research on the use of mathematical modeling to analyze the effects of cannibalization. This research can be separated into three general approaches: reliability and stochastic analysis, inventory-based models, and simulation (queuing) analysis. Initially, research on the effects of cannibalization analyzed the reliability of a system under total, instantaneous cannibalization. These methodologies typically derive general expressions for computing system reliability, but they do not provide numerical examples. Other than Fisher [7], these models do not compare competing cannibalization policies and primarily focus on mathematical formulation. One of the first mathematical studies of cannibalization is described by Hirsh et al [9]. They develop an expression for the expected value of system status as a function of the number of working parts of each type. Simon [14] extends the methodology proposed by Hirsh et al by allowing restrictions on the interchangeability of parts. Hochberg [10] further extends the research of Hirsch et al and Simon by allowing k states of part operability instead of assuming a binary (working/failed) representation. Fisher [7] models the process of repairing or cannibalizing a part using continuous-time Markov chains.

Several other cannibalization models seek to optimize spare part inventories. Some of these models address the possibility of allowing cannibalization actions to compensate for a lack of spare parts. Sherbrooke [12] develops METRIC (Multi-Echelon Technique for Recoverable Item Control), a mathematical model utilizing Bayesian probability theory for estimating base and depot stock levels for recoverable items. Spare levels are allocated by optimizing the minimum expected number of backorders for all bases. Although cannibalization actions are modeled explicitly, this study serves the foundation for several future studies. Following the development of METRIC, Sherbrooke [13] develops NORS, another model that estimates the expected number of aircraft not operationally ready at a random point in time due to supply. Even though this model does address cannibalization, only a single-echelon system is addressed. Muckstadt [11] proposes MOD-METRIC, an extension of METRIC that allows a hierarchical or multiple-

4

indentured parts structure. Fisher [5] extends Sherbrooke's and Muckstadt's research by developing an optimization model for a two-echelon, two-indenture system with and without cannibalization. Fisher's main objective of this study is to develop an analytical model that helps validate future, more complex simulation models that he develops.

In several studies, Fisher [3, 4, 6] uses computer simulation to model the effects of cannibalization and to recommend cannibalization policies. Since analytical results are not the goal, these studies can and do relax several restrictive assumptions (e.g., total, instantaneous cannibalization) of previous cannibalization studies rendering more practical results for decision makers. These simulation models are open-network models, i.e. failed systems (demand) enter the model as new entities and repaired systems permanently depart the model. Since overall performance, e.g. readiness of an aircraft fleet, cannot be estimated under these conditions, the development of a closed-network simulation model is a beneficial extension to previous cannibalization research.

3 The Generic Analysis

The goal of the generic portion of this project is to create a multi-echelon, closed-network, discrete-event simulation model to study the effects of cannibalization and spare parts levels on the readiness of a set of systems; however, our intention is not to model and analyze a real set of systems. Rather, our purpose is to define, model and analyze a hypothetical set of systems that captures many (but not all) of the issues related to cannibalization.

3.1 Scenario Definition

In this section, the reliability and maintainability characteristics of the set of systems (*Table 3.1*) and the associated logic are summarized. This logic is also captured in *Figure 3.1*, *Figure 3.2* and *Figure 3.3*.

Consider a set of m systems with each system being a two-component ($n = 2$) series system. Throughout their useful life of length u, the systems operate continuously until they fail. When operating, component j has a constant failure rate of λ_j. Thus, the operating time to failure of a system is an exponential random variable having rate $\lambda_1 + \lambda_2$. When a component fails, the system fails and is immediately routed to its base of operations. A maintenance technician is dispatched to the system and determines which maintenance actions are required. We assume an unlimited number of maintenance technicians with travel and diagnosis time included in the maintenance action times.

Let j denote the type of component that failed, $j = 1$ or 2. First, the maintenance technician removes the failed component (maintenance action $k = 1$) in D_{1j} time units. If a spare component j is available, then the spare is installed (maintenance action $k = 2$) and the system is returned to operation. Note that the installation of the spare consumes D_{2j} time units.

If no spare component j is available and cannibalization is allowed ($x = 1$), the maintenance technician checks for other failed systems that have a functional component j. If such systems are available, then one is selected at random and the functional component j is cannibalized (maintenance action $k = 3$) and installed on the system of interest. The system is then returned to

operation. Note that the cannibalization action consumes D_{3j} time units. If cannibalization is not permitted ($x = 0$) or not possible, then the failed system must wait for a repaired component j to become available. Note that cannibalized systems are waiting for both types of components.

Finally, the maintenance technician determines if the removed component j can be repaired on-site. The probability that on-site repair is possible is δ_j. On-site repair (maintenance action $k = 4$) consumes D_{4j} time units. If on-site repair is not possible, then the failed component is sent to an off-site location for repair with a lead time of L_j.

Table 3.1: Reliability and Maintainability Parameters

Component	1	2
λ_j	1/600	1/1300
L_j	60, 95, 130	135, 172, 238
D_{1j}	2, 6, 10	8, 9.5, 11
D_{2j}	3, 6, 9	5, 11, 17
D_{3j}	10, 18, 26	13, 17.5, 22
D_{4j}	30, 40, 50	78, 120, 186
δ_j	20%	25%
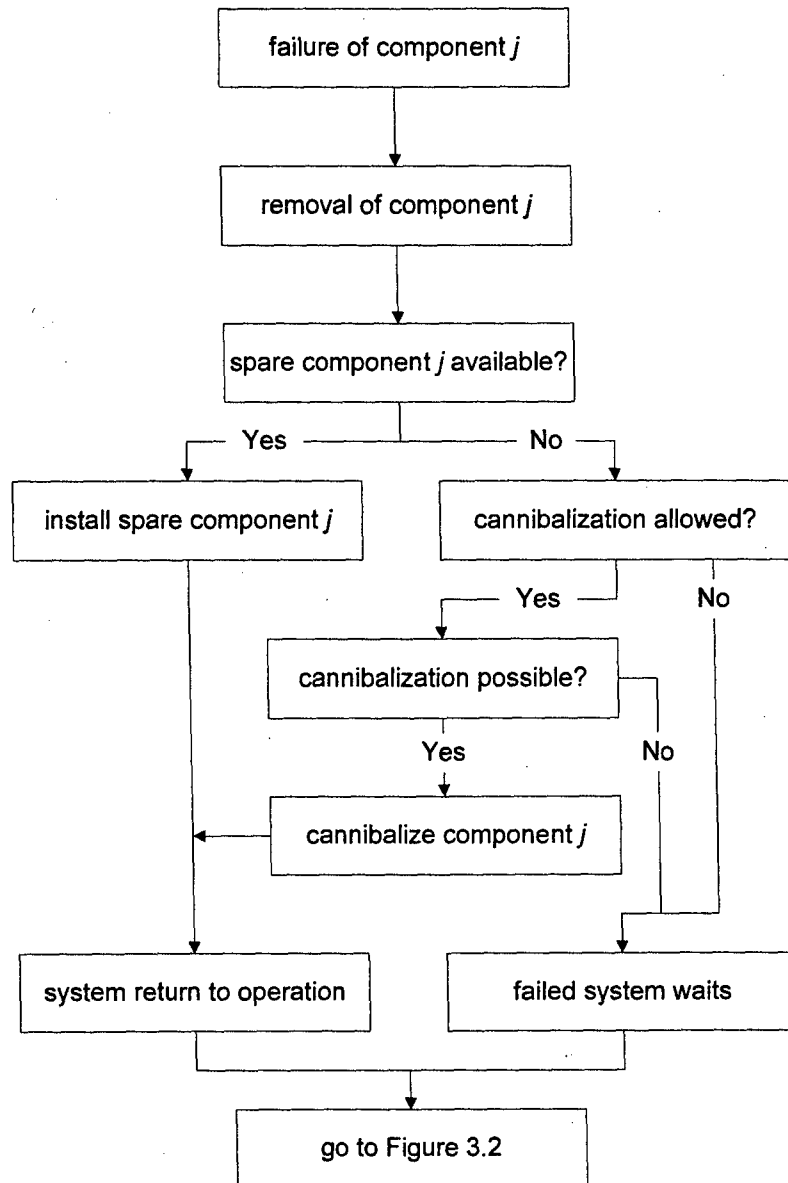
Figure 3.1: Maintenance Logic, Part 1

```
                    ┌──────────────────────┐
                    │  on-site repair possible? │
                    └──────────────────────┘
                               │
              ┌──── Yes ───────┴────── No ────┐
              ▼                                ▼
    ┌──────────────────┐          ┌──────────────────┐
    │   on-site repair  │          │   off-site repair │
    └──────────────────┘          └──────────────────┘
              │                                │
              └────────────┬───────────────────┘
                           ▼
                 ┌──────────────────┐
                 │  go to Figure 3.3 │
                 └──────────────────┘
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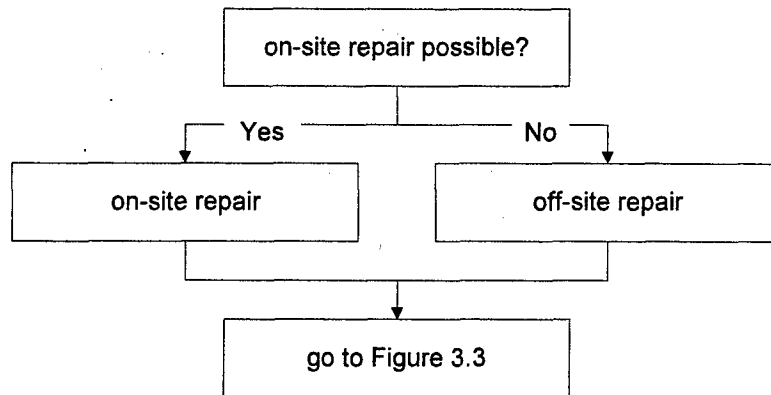**Figure 3.2: Maintenance Logic, Part 2**

When a repaired component j returns from the off-site depot or from on-site repair, the following logic is used to determine its disposition.

♦ Install the component on a waiting system that only needs component j. Return the system to operation.

♦ Restore a cannibalized system that is waiting for both components using this component and a spare of the other type.
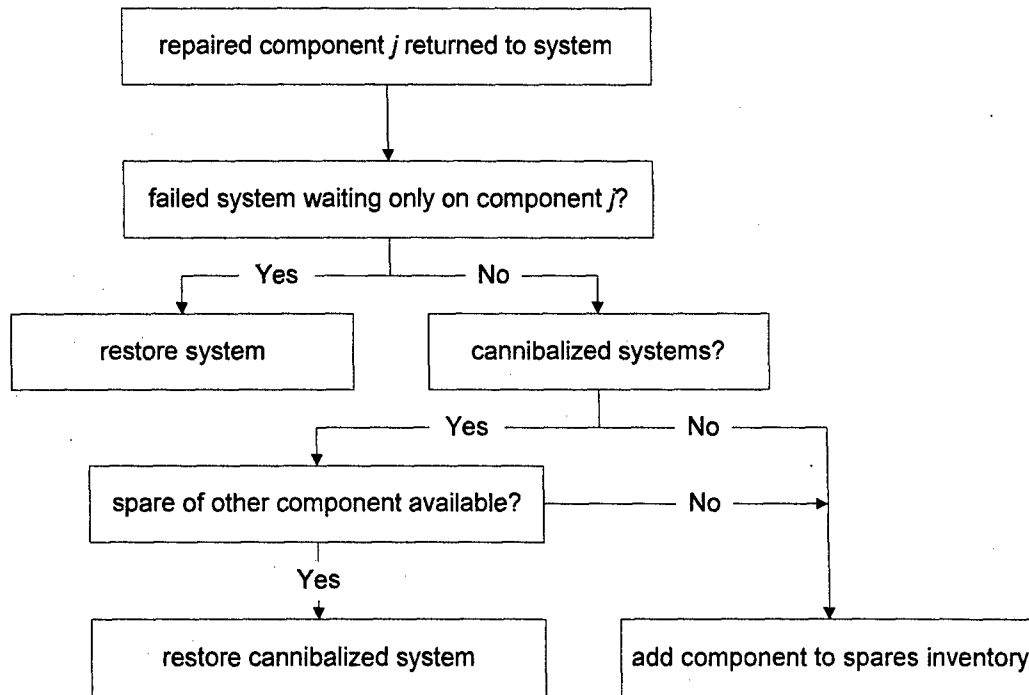
♦ Add the component to the spare parts inventory.

Figure 3.3: Maintenance Logic, Part 3

3.2 Simulation Modeling

A discrete-event simulation model of the defined scenario was developed using the simulation language Arena. The parameters for the model are the initial number of spare components of each type (s_1 and s_2) and whether or not cannibalization actions are allowed at the site (x). After specification of these parameters, the simulation model is executed using a run length of u and a specified number of replications. The collected statistics of interest are: the average readiness of aircraft, and the ratio of maintenance man hours to total operational hours.

3.3 Numerical Example

A discrete-event simulation model of the defined scenario was developed using the simulation language Arena. The parameters for the model are the initial number of spare components of each type (s_1 and s_2) and whether or not cannibalization actions are allowed at the site (x). After specification of these parameters, the simulation model is executed using a run length of u and a

specified number of replications. The collected statistics of interest are: the average readiness of aircraft and the ratio of maintenance man hours to total operational hours.

Due to space limitations at the maintenance facility, initial spare inventory levels are limited to s_1 ≤ 2 and $s_2 \leq 1$. As a result, there are 12 unique combinations of s_1, s_2, and x that correspond to different maintenance policies. Fifty replications of the simulation model were performed for each feasible solution to obtain the statistics of interest. The average readiness (Readiness) and the average maintenance man hours per operating hour (MMH_OH) estimates for this example are provided in *Table 3.2* and *Table 3.3*.

Table 3.2: Performance Estimates with Cannibalization

s_1	s_2	Readiness	MMH_OH
0	0	80.6 %	0.0649
0	1	83.6 %	0.0629
1	0	83. 9 %	0.0629
1	1	88.4 %	0.0613
2	0	85.4 %	0.0607
2	1	90.8 %	0.0589

Table 3.3: Performance Estimates without Cannibalization

s_1	s_2	Readiness	MMH_OH
0	0	77.7 %	0.0567
0	1	82.6 %	0.0565
1	0	82.7 %	0.0564
1	1	88.0 %	0.0567
2	0	85.2 %	0.0569
2	1	90.7 %	0.0568

Several important results are obtained from this example, and these results are consistent with the results obtained from all numerical examples studied. First, with no spares and no cannibalization, the set of systems does not meet its readiness target. Second, the use of cannibalization enables the set to meet its goal with a significant increase in labor; however, the readiness goal can also be met without cannibalization if one spare of either type is held initially at the maintenance facility. In this case, the readiness goal is met without the significant increase in labor requirements. Obviously, this trade-off must be addressed by the decision maker.

4 The Hill-Based Analysis

The generic effort provides a valuable portrayal of the type of analysis that can be conducted for the purpose of evaluating cannibalization practices using simulation modeling; however, the generic model requires too much detail to be immediately beneficial. Therefore, the goal of this portion of the project is to develop a higher-level, discrete-event simulation model of a more realistic scenario that can be used to evaluate cannibalization issues typically faced in USAF settings.

4.1 The Hill AFB Visit

Through discussions with our (Air Force Research Laboratory (AFRL) contacts, Hill AFB was identified as the appropriate location for our research team to learn about the relevant cannibalization practices and issues. In March 2003, two members of the research team visited Hill AFB and learned a tremendous amount about these practices and issues. As a result of this visit and additional discussion with AFRL personnel, three "motivating questions" were identified.

♦ Should cannibalization actions be consolidated or should they be conducted at the AMU level?

♦ If cannibalization actions are consolidated, how many aircraft should be designated as CANN birds?

♦ If cannibalization actions are consolidated, how long should aircraft be held as CANN birds?

These questions served to guide our efforts relative to the development (in Arena) and analysis of the simulation models. Note that two simulation models are required, one for the case in which cannibalization actions are consolidated (the Consolidated Model) and one for the case in which cannibalization actions are not consolidated (the AMU Model). Both simulation models track the operations and maintenance of 72 aircraft (three squadrons of 24 aircraft each). The values for the input parameters used in the simulation effort were determined from the Hill visit and further discussions with AFRL personnel.

4.2 The Consolidated Model

We initiated our modeling efforts with the Consolidated Model. In this model, an initial set of CANN birds (the number being specified by the user) is randomly selected from the 72 aircraft. The remaining aircraft are then deployed on 24-hour missions. Upon return from a mission, one maintenance technician transports an aircraft to the AMU in an amount of time that is a triangular random variable having a minimum of three hours, a mode of five hours, and a maximum value of six hours. For future reference, note that we denote this elapsed time as T(3,5,6). At this point, the technicians determine if the aircraft is mission capable (the probability of being mission capable is 85%). If the aircraft is mission capable, then routine maintenance is performed by a technician in T(1,3,5) hours and the aircraft is sent on another mission.

If the aircraft is not mission capable, then diagnostics or slaving are used to determine whether or not the aircraft can be repaired on base. Note that slaving is required 20% of the time and each slaving attempt is 90% successful, requires one or two technicians, and consumes T(2,5,6) hours. Note the diagnostics requires one technician for T(2,3,4) hours. Ultimately, 30% of non-mission-capable aircraft can be repaired on base. On-base repair requires two or three technicians for T(12,24,36) hours. Note that any time a technician is required, there is a 25% chance that skill level 3 is required and a 50% chance that skill level 2 is required.

If on-base repair is not possible, each CANN bird is checked for the necessary parts. Without going into the details, the model utilizes a mathematical function that decreases the usefulness of a CANN bird as it remains in the CANN dock. If possible, a cannibalization action requires two or three technicians for T(10,12,24) hours. If cannibalization is not possible, then the aircraft must wait T(72,120,168) hours for the repaired part to return from the depot.

When an aircraft has been on the CANN dock for the user-specified number of days, the next returning aircraft is transported to the CANN dock by a single technician in T(3,5,6) hours. This aircraft is designated as a new CANN bird and used to rebuild the current CANN bird. According to the model, the rebuild occurs either with or without a "problem." Without a problem, the rebuild requires two or three technicians for T(24,36,48) hours. With a problem, the rebuild requires three technicians for T(120,192,264) hours. Without going into the details, the

model utilizes a mathematical function that increases the probability of a problem as the time as a CANN bird increases.

The simulation model is executed using 50 one-year replications. The statistics collected by the simulation model are average aircraft readiness (Readiness) and average maintenance man hours per flight hour (MMH_FH).

4.3 The AMU Model

The logic for the AMU Model is identical to the Consolidated Model with one exception. Instead of a single CANN dock with a specified number of CANN birds, each AMU has its own CANN bird.

4.4 Addressing the Motivating Questions

Recall the first motivating question: Should cannibalization actions be consolidated or should they be conducted at the AMU level? To address this question, we compare the Consolidated Model with two CANN birds to the AMU Model with one CANN bird at each AMU. In both cases, we use a CANN bird duration of 45 days. The Consolidated Model yields a Readiness of 81.5% (MMH_FH = 0.1234) whereas the AMU Model yields a Readiness of 75.3% (MMH_FH = 0.13229). As expected, the results imply that consolidated cannibalization results in superior readiness with less required labor.

Recall the second motivating question: If cannibalization actions are consolidated, how many aircraft should be designated as CANN birds? To address this question, we use a CANN bird duration of 45 days and execute the model for each of one, two, three and four CANN birds. The results, summarized in *Table 4.1*, indicate that the appropriate number of CANN birds is two.

Table 4.1: Number of CANN Birds

Number of CANN Birds	Readiness	MMH_FH
1	78.1%	0.1256
2	81.5%	0.1234
3	80.6%	0.1242
4	78.4%	0.1269

Recall the third motivating question: If cannibalization actions are consolidated, how long should aircraft be held as CANN birds? To address this question, we use two CANN birds and execute the model for CANN bird durations of each of 30, 35, ... 60 days. The results, summarized in *Table 4.2*, indicate that the appropriate CANN bird duration is 30 days.

Table 4.2: CANN Bird Duration

CANN Bird Duration	Readiness	MMH_FH
30 days	83.4%	0.1199
35 days	83.1%	0.1208
40 days	82.1%	0.1227
45 days	81.5%	0.1234
50 days	80.5%	0.1248
55 days	79.7%	0.1252
60 days	78.8%	0.1247

5 Future Opportunities

The research conducted in this project provides numerous opportunities for future work. First, cannibalization is used for more than military aircraft. Cannibalization is utilized on many types of systems in many industries. We intend to explore the issues related to cannibalization in other industries. In fact, some members of the research team have already conducted a small-scale study into the effects of cannibalization on the performance of simple manufacturing systems.

Second, cannibalization is one of many maintenance policies that can be specified, analyzed and optimized. Unfortunately, in this and most other studies, cannibalization is studied independently of these other policies. We intend to explore linkages between cannibalization policies and preventive maintenance policies including opportunistic and selective maintenance.

Third, the generic model provides the analysis of cannibalization at the component level, whereas the Hill-based models provide the analysis at the system level. We intend to continue our study of cannibalization by conducting a multi-year effort into the development of large-scale cannibalization models that utilize a component-level view. Such models would provide a more complete picture of the benefits and detriments of cannibalization practices.

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